TORQUE SENSING APPARATUS FOR PICKING UP A MAGNETIC FLUX

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation-in-part of United States Patent Application 10/402,620 filed on March 28, 2003.

BACKGROUND OF THE INVENTION

1) Field of the Invention

[0002] The subject invention relates to torque sensing apparatus and, in particular, an apparatus and method for sensing movement and rotation of a shaft.

2) Description of Related Art

[0003] In systems having rotating drive shafts it is sometimes necessary to know the torque and speed of these shafts in order to control the same or other devices associated with the rotatable shafts. Accordingly, it is desirable to sense and measure the torque applied to these items in an accurate, reliable and inexpensive manner. Sensors to measure the torque imposed on rotating shafts, such as but not limited to shafts in vehicles, are used in many applications. For example, it might be desirable to measure the torque on rotating shafts in a vehicle's transmission, or in a vehicle's engine (e.g., the crankshaft), or in a vehicle's steering system for a variety of purposes known in the art.

[0004] One application of this type of torque measurement is in electric power steering systems wherein an electric motor is driven in response to the operation

and/or manipulation of a vehicle steering wheel. The system then interprets the amount of torque or rotation applied to the steering wheel and its attached shaft in order to translate the information into an appropriate command for an operating means of the steerable wheels of the vehicle.

[0005] Prior methods for obtaining torque measurement in such systems were accomplished through the use of contact-type sensors directly attached to the shaft being rotated. For example, one such type of sensor is a "strain gauge" type torque detection apparatus, in which one or more strain gauges are directly attached to the outer peripheral surface of the shaft and the applied torque is measured by detecting a change in resistance, which is caused by applied strain and is measured by a bridge circuit or other well-known means.

[0006] Another type of sensor used is a non-contact torque sensor wherein magnetostrictive materials are disposed on rotating shafts and sensors are positioned to detect the presence of an external flux which is the result of a torque being applied to the magnetostrictive material.

[0007] Such magnetostrictive materials require an internal magnetic field which is typically produced or provided by either pre-stressing the magnetostrictive material by using applied forces (e.g., compressive or tensile). The magnetic field is circumferential either in a clockwise or counter clockwise direction as a result of a hoop stress. Alternatively, an external magnet or magnets are provided to produce the same or a similar result to the magnetostrictive material.

[0008] To this end, magnetostrictive torque sensors have been provided wherein a sensor is positioned in a surrounding relationship with a rotating shaft, with an air gap

being established between the sensor and shaft to allow the shaft to rotate without rubbing against the sensor. A magnetic field is generated in the magnetostrictive material by passing a pulse of high-intensity electric current through an electrical conductor located inside the shaft. This results in a pulsed magnetic field that permeates the magnetostrictive material and magnetizes it. The electrical conductor is then removed, and the magnetostrictive material remains magnetized, i.e. it hosts a permanent magnetic field. Applying torque to the shaft changes direction of this magnetic field. A fraction of this field closes a loop through a set of magnetic field sensors located outside the magnetostrictive material.

[0009] The output of the magnetic field sensors is an electrical signal that depends on the total magnetic reluctance in the above-described loop. Part of the total magnetic reluctance is established by the air gap, and part is established by the shaft itself. The magnetic field through the magnetic sensors, changes as a function of torque applied to the shaft. Thus, changes in the output of the magnetic sensors can be correlated to the torque experienced by the shaft. Magnetic field sensors are typically Hall sensors.

[0010] As understood herein, the air gap, heretofore necessary to permit relative motion between the shaft and sensor, nonetheless undesirably reduces the sensitivity of conventional magnetostrictive torque sensors. As further understood herein, it is possible to minimize the air gap between a shaft and a magnetostrictive torque sensor, thereby increasing the sensitivity of the sensor vis-a-vis conventional sensors. Moreover, the subject invention recognizes that a phenomenon known in the art as

"shaft run-out" can adversely effect conventional magnetostrictive torque sensors, and that a system can be provided that is relatively immune to the effects of shaft run-out.

[0011] Accordingly, the related art assemblies and methods are characterized by one or more inadequacies. Therefore, it would be advantageous to provide a torque sensing apparatus that senses and measures an applied torque in an accurate, reliable, and inexpensive manner. Further, it would be advantageous to provide the torque sensing apparatus substantially free of outside magnetic interference.

BRIEF SUMMARY OF THE INVENTION

[0012] The subject invention provides a torque sensing apparatus for picking up a magnetic flux flowing from edges of a magnetostrictive material disposed on a shaft. The apparatus includes a first flux collector and a second flux collector spaced from each other and extending annularly around the shaft to define a gap therebetween. A first fluxgate is connected to the first flux collector at one end and to the second flux collector at the other end. A first excitation coil is wound about the first fluxgate and a feedback coil is positioned in the gap such that the feedback coil is wound within the flux collectors, the first fluxgate, and the excitation coil.

[0013] The subject invention overcomes the inadequacies that characterize the related art assemblies and methods. Specifically, the subject invention provides an accurate, reliable, and inexpensive apparatus for sensing torque that is substantially free from outside magnetic interference. Since the feedback coil is wound within the flux collectors, the first fluxgate, and the excitation coil, the subject invention minimizes interaction of flux from the feedback coil interacting with any shields resulting in a more stable flux measurement.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING

[0014] Other advantages of the subject invention will be readily appreciated as the same becomes better understood by reference to the following detailed description when considered in connection with the accompanying drawings wherein:

[0015] Figure 1 is a perspective view of a torque sensing apparatus of the subject invention disposed about a shaft having a magnetostrictive material;

[0016] Figure 2 is a cross-sectional side view of the torque sensing apparatus having a shield positioned adjacent the apparatus;

[0017] Figure 3 is a perspective view of a fluxgate having a coil positioned along the fluxgate;

[0018] Figure 4A is a graph of the BH curve of the fluxgate of the torque sensing apparatus of the subject invention with no torque applied to the shaft;

[0019] Figure 4B is a graph of the BH curve of the fluxgate of the torque sensing apparatus of the subject invention with torque applied to the shaft, but with no current in the feedback coil;

[0020] Figure 5 is a graphical illustration of the time dependence of the voltage across the excitation coils and the feedback coil for no torque applied to the shaft;

[0021] Figure 6 is a graphical illustration modeling the theoretical time dependence of the voltage across the excitation coils and the feedback coil for torque applied to the shaft, but with no current in the feedback coil;

[0022] Figure 7 is a graphical illustration modeling an experimentally measured voltage waveform on the feedback coil when a sinusoidal voltage is applied to the excitation coils in the presence of a torque flux, but with no current in the feedback coil;

[0023] Figure 8 is a graphical illustration of a measured voltage waveform by the feedback coil when a sinusoidal voltage is applied to the excitation coils and a direct current is applied to the feedback coil to cancel out the torque flux;

[0024] Figure 9 is a graphical illustration of a direct current component of an output voltage on the feedback coil versus an applied torque; and

[0025] Figure 10 is a circuit diagram according to the subject invention.

DETAILED DESCRIPTION OF THE INVENTION

[0026] Referring to the Figures, wherein like numerals indicate like or corresponding parts throughout the several views, a torque sensing apparatus for picking up a magnetic flux is shown generally at 20 in Figure 1. The apparatus **20** includes a torque-subjected member illustrated in the form of a cylindrical shaft **22**. However, the subject invention is not intended to be limited to the specific configurations illustrated in Figure 1. The shaft **22** preferably comprises a non-magnetic material, such as a stainless steel or aluminum. As shown, the apparatus **20** is disposed in a surrounding relationship with the shaft **22** to sense the torque imposed on the shaft **22**. In one exemplary embodiment, the shaft **22** is a rotating shaft within a vehicle. For instance, the shaft **22** can be a steering column shaft, engine shaft, or transmission shaft, although it is to be appreciated that the principles set forth herein apply equally to other vehicular and non-vehicular rotating shafts.

[0027] A magnetostrictive material **24** is disposed on the surface of the shaft **22**. The magnetostrictive material **24** is coated on or applied to the shaft **22** in a manner that will produce a flux signal when the torque is applied to the shaft **22**. The same signal is collected by the torque sensing apparatus **20** for measuring the torque applied to the shaft **22**. An example of the magnetostrictive material **24** is of the type disclosed in U.S. patent No. 6,645,039, the contents of which are incorporated herein by reference thereto. Of course, other types of magnetostrictive materials **24** are contemplated to be used in accordance with the subject invention. The

magnetostrictive material **24** may be applied by spraying techniques such as, but not limited to, thermal spraying or kinetic spraying. The magnetostrictive material **24** typically includes, but is not limited to, magnetostrictive particles selected from one of iron, iron alloys, ingot rare earth composites, nickel, and terfenol and magnetic particles with coercivity selected from AlNiCo5 magnets and melt spun terfenol.

[0028] The magnetostrictive material **24** is magnetically polarized to have a circumferential moment in a first direction, such as in clockwise or counterclockwise direction about the shaft **22**. Of course, the magnetostrictive material **24** may be magnetically polarized in an opposite direction as will be appreciated by those skilled in the art. Upon receipt of an applied torque, a longitudinal, or axial, magnetic flux or torque flux leaves the magnetostrictive material **24**. This flux is proportional to the torque that will be picked up by the torque sensing apparatus **20**. In other words, the torque flux flows from edges of the magnetostrictive material **24**.

[0029] Referring now in particular to Figures 1 and 2, a first flux collector **26** and a second flux collector **28** are shown spaced from each other. The first and second flux collectors **26, 28** extend annularly around the shaft **22**. A gap **30** is defined between the shaft **22** and the first and second flux collectors **26, 28**. The first and second flux collectors **26, 28** are constructed out of a high-permeable material such as metalglass, permalloy, mumetal, or other materials having equivalent characteristics. As will be discussed herein, the configuration of the first and the second flux collectors **26, 28** allow the flux collectors to pick up torque flux signals anywhere along the periphery of magnetostrictive material **24**.

[0030] A first fluxgate **32** is connected to the first flux collector **26** at one end and to the second flux collector **28** at the other end. The first fluxgate **32** has a first excitation coil **34** wound about the first fluxgate **32**. Preferably, the apparatus **20** includes a second fluxgate **36** connected to the first flux collector **26** at one end and to the second flux collector **28** at the other end, opposite the first fluxgate **32** in Figure 1. Figure 3 illustrates one embodiment of the second fluxgate **36**. Preferably, the first and the second fluxgate **32, 36** are similarly shaped with the most preferred shape shown in Figure 3. A second excitation coil **38** is wound about the second fluxgate **36**. Preferably, the first and second excitation coils **34, 38** are connected in series, as will be described in more detail below. Preferably, the first and second flux collectors **26, 28** and the first and second fluxgates **32, 36** are constructed of a high-permeable material. Most preferably, the first and second excitation coils **34, 38** are formed from copper. It is to be appreciated that either the first and second excitation coils **34, 38** may also be used to detect a signal, which may be referred to as pick-up coils by those skilled in the art.

[0031] In the most preferred embodiment, the first and second flux collectors **26, 28** and the first and second fluxgates **32, 36**, with the respective excitation coils **34, 38**, are integrally formed as a sleeve unit **40**. The shaft **22** and the magnetostrictive material **24** are freely rotatable inside the sleeve unite **40**. As will be described herein, the sleeve unit **40** is adapted to measure the torque flux of the shaft **22**. The sleeve unit **40** is constructed of a non-conductive material such as plastic, nylon or polymer of equivalent properties, which is lightweight and easily molded or

manufactured. In addition, the sleeve unit **40** may be secured to a structure (not shown) that is stationary with respect to the shaft **22**.

[0032] Further, a shield **42** is positioned about the sleeve unit **40**, shown in Figure 2. The shield **42** prevents the apparatus **20** from being affected by external magnetic fields, such as the Earth's magnetic field or fields present from other electronic devices, such as within a vehicle. This allows the apparatus **20** to be substantially free of outside magnetic interference. However, it is to be appreciated that the apparatus **20** still functions without the shield **42** and that the shield **42** may be formed of any structure, such as an entire engine compartment of the vehicle and still prevent magnetic interference.

[0033] The subject invention also includes a feedback coil **44** positioned in the gap **30** between the sleeve unit **40** and the shaft **22**. It is to be appreciated that the feedback coil **44** may be formed integrally with the sleeve unit **40**, in which case, the feedback coil **44** is between the shaft **22** and the flux collectors **26**, **28**, the fluxgates **32, 36**, and the excitation coils **34, 38**. By positioning the feedback coil **44** within the gap, any flux generated in the feedback coil **44** is prevented from interacting with outside interference, such as the shield **42** or vehicle. The flux collectors **26, 28**, the fluxgates **32, 36**, and the excitation coils **34, 38** act to limit the amount of flux leakage from the feedback **44** to these outside interferences. When the feedback coil **44** is wound about and on the outside of the sleeve unit **40**, then the flux generated by the feedback coil **44** interacts with the shield **42** which effects the measurement of the torque being applied to the shaft **22**. Therefore, the positioning the feedback coil **44**

between the sleeve unit **40** and the shaft **22** is important to accurately detect and measure the torque being applied.

[0034] Referring to Figure 10, a detection circuit **46** is shown for determining a torque applied to the shaft **22**. The detection circuit **46** includes a voltage source **48** for applying a voltage to the first and second excitation coils **34, 38** at a first frequency. A frequency doubler **50** may be used for doubling the first frequency to a second frequency and for producing an output signal relating to the voltage sensed across the feedback coil **44**. The detection circuit **46** further includes a lock-in amplifier **52** for receiving signals related to a second harmonic voltage waveform on the feedback coil **44** and for receiving a reference signal from the frequency doubler **50**. The output signal is received by a voltage to current converter **54** configured to receive the output voltage from the lock-in amplifier **52** and convert it to a current. The current in the feedback loop is driven to zero out the total flux that is applied to the first fluxgate **32** and the second fluxgate **36**.

[0035] The feedback coil **44** is configured to receive magnetic flux from the shaft **22** with the magnetostrictive coating **22** and also to generate a feedback flux proportional to the current put out by the converter **54**. Thus, the apparatus **20** is capable of maintaining the fluxgate material out of magnetic saturation wherein an applied torque will create a torque flux that will be picked up by the apparatus **20**. When the fluxgate material is out of saturation, there is no 2^{nd} harmonic waveform (current or voltage). This is the case, e.g., when no torque flux is generated by the shaft **22**. When torque is applied to the shaft **22**, there is a torque flux and a second harmonic signal appears at the output of the lock-in amplifier **52**. The converter **54**

then sends a current which creates a feedback flux. When the feedback flux exactly compensates the torque flux, the second harmonic signal of the output of the lock-in amplifier **52** is zero, and there is equilibrium. Thus, the subject invention uses the 2^{nd} harmonic waveform (current or voltage) to provide a signal that is used to provide a nullifying current to the feedback coil **44**.

[0036] As discussed above, when the torque is applied to the shaft **22**, the longitudinal magnetic torque flux leaves the coating of magnetostrictive material **24**, and the sleeve unit **40** provides this flux with a return path. The produced torque flux, if existing, is picked up by the first flux collector **26**, passes through the first and second fluxgates **32, 36** and the second flux collector **28** to the other side of the magnetostrictive material **24**. The feedback flux subtracts from the torque flux produced by the feedback coil **44**. The current from the converter **54** that flows through the feedback coil **44** is then as a measurement of the applied torque.

[0037] Referring to Figures 4A, a flux density (B) versus a magnetization force, or field intensity (H) curve for the fluxgate **36** is illustrated without torque being applied to the shaft **22**. The material used to form the fluxgates **32, 36** reaches magnetic saturation when subject to a strong enough magnetic field. Saturation is illustrated as a plateau in Figures 4A and 4B. The excitation current through the coils 34, 38 results in an excitation field as shown in Figures 4A and 4B.

[0038] Referring to Figure 4B, a flux density (B) versus a magnetization force, or field intensity (H) curve for the sleeve unit **40** is illustrated with torque being applied to the shaft **22**. The application of torque to the shaft **22** results in the torque flux which adds to the excitation field of Figure 4A and shifts the field so as to cause

magnetic saturation of the fluxgates **32, 36**. The saturation is achieved in one direction when the torque is applied in one direction and in the opposite direction when the torque is applied in the opposite direction.

[0039] Figure 5 illustrates the time dependence of the voltage across the excitation coils and feedback coil **44** without torque being applied to the shaft **22**. The first and the second excitation coils **34, 38** are connected in series and are excited by a high frequency sinusoidal voltage to generate magnetic flux. The sinusoidal voltage and the frequency are adjusted such that the passing flux through the first and second fluxgates **32, 36** and the first and second flux collectors **26, 28** does not cause saturation without torque flux. The sinusoidal voltage and frequency are adjusted such that the first and second flux gates are just below the saturation limit, as discussed above. Figure 6 illustrates the time dependence of the voltage across the excitation coils and feedback coil **44** with torque being applied, but when the converter **54** is disconnected.

[0040] In operation, torque is applied to the shaft **22** in either a clockwise direction or a counterclockwise direction. Torque can be applied while the shaft **22** rotates freely inside the sleeve unit **40**. When the torque is applied, the torque flux generated by the material **24** is sensed by the flux collectors **26, 28** and passed through the fluxgates **32, 36**.

[0041] In the coil arrangement of Figure 1, the induced voltage in the feedback coil **44** contains a 2^{nd} harmonic component upon application of the torque to the shaft **22**, as illustrated in Figures 6 and 7. This 2^{nd} harmonic voltage is extracted by a means of the lock-in amplifier **52** and rectified and fed, as current, to the feedback

coil **44** via the voltage to current converter **54** to nullify the 2nd harmonic component. This current through the feedback coil **44** is proportional to the torque applied to the shaft **22**.

[0042] In addition, and due to the circular configuration of the flux collectors **26, 28**, the apparatus **20** is capable of integrating the magnetic flux about the entire periphery of the magnetostrictive material **24**. Accordingly, the torque moment is measured about the entire periphery of the magnetostrictive material **24** by integrating along the circumference at either end of the magnetostrictive material **24**. This allows the apparatus **20** to measure the torque moment of the shaft **22** regardless of angle at which the shaft **22** is positioned. In addition and by integrating along the circumference at either end of the magnetostrictive material **24**, the apparatus **20** is self-correcting or is not susceptible to measurement anomalies associated with shaft **22** wobble or irregularities in the surface of the shaft **22** or magnetostrictive material **24** disposed on the shaft **22**.

[0043] Figure 7 is a graphical illustration of a 2nd harmonic component and Figure 8 is a graphical illustration of a suppressed 2nd harmonic component when the feedback current is produced by the converter **54** and sent into the feedback coil **44**. It is important to maintain the fluxgates **32, 36** near saturation, because this causes the 2nd harmonic voltages in the feedback coil **44**, as well as DC offset in the excitation coils. Therefore, and in one embodiment, the applied torque is proportional to the feedback current that nullify the 2nd harmonic voltage of the feedback coil **44**.

[0044] A signal relating to the DC current sent to the feedback coil **44** is also sent to a microprocessor, controller or equivalent means (not shown) having a look up

table or other means for determining the applied torque, which is used in any vehicular or other control system requiring torque readings.

[0045] In a most preferred embodiment, the first excitation coil **34** comprises 50 turns of 32 gage wire and the second excitation coil **38** comprises 50 turns of 32 gage wire, while the feedback coil **44** comprises 72 turns of 25 gage wire. Of course, and as applications require the gage of the wire and number of turns may vary. In the illustrated embodiment, an AC voltage of 1.8 volts at a 49 frequency of kilohertz is applied to the first and second excitation coils **34, 38**. In addition, this voltage is also applied to a frequency doubler **50** that doubles the frequency and applies a 98 kilohertz frequency as a reference input into a lock-in amplifier **52**, which is used as a bandpass filter. Accordingly, only voltages at the reference frequency (98 kHz, i.e. double the excitation frequency) will be picked up. Of course, and as applications require the frequency and the magnitude of excitation voltage may vary depending on the design of the flux gate.

[0046] The feedback coil **44** voltage is passed through the lock-in amplifier **52** to extract a rectified 2^{nd} harmonic component voltage, which is then inputted into the voltage to current converter **54**. This converted voltage is then inputted as DC current in the feedback coil **44** to nullify the saturation caused by the torque flux. The rectified 2^{nd} harmonic component voltage is proportional to the applied shaft **22** torque. Figure 9 is a graphical illustration of a plot of the 2^{nd} harmonic component voltage on the feedback coil **44** versus an applied torque to the shaft **22**.

[0047] Obviously, many modifications and variations of the subject invention are possible in light of the above teachings. The invention may be practiced otherwise than as specifically described within the scope of the appended claims.